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X-652-73-335
PREPRINT

NASA TM X-70515

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T. SCHMUGGE
T. T. WILHEIT
P. GLOERSEN
M. F. MEIER
D. FRANK
I. DIRMHIRN





NOVEMBER 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

(NASA-TM-X-70515) MICROWAVE SIGNATURES OF SNOW AND FRESH WATER ICE (NASA) 15 p HC $3.00 CSCL 08L

N74-10381

Unclas
G3/13 22091

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T. Schmugge, T. T. Wilheit, and P. Gloersen
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

M. F. Meier and D. Frank
Water Resources Division
U.S. Geological Survey
Tacoma, Washington

I. Dirmhirn
Utah State University
Logan, Utah

"Presented at the Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources"

November 1973



GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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T. Schmugge, T. T. Wilheit, and P. Gloersen
NASA/Goddard Space Flight Center
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## ABSTRACT

During March of 1971, the NASA Convair 990 Airborne Observatory carrying microwave radiometers in the wavelength range 0.8 to 21 cm was flown over dry snow with different substrata: Lake ice at Bear Lake in Utah; wet soil in the Yampa River Valley near Steamboat Springs, Colorado; and glacier ice, firn and wet snow on the South Cascade Glacier in Washington. The data presented indicate that the transparency of the snow cover is a function of wavelength. False-color images of microwave brightness temperatures obtained from a scanning radiometer operating at a wavelength of 1.55 cm demonstrate the capability of scanning radiometers for mapping snowfields.

## INTRODUCTION

In order to obtain data on the microwave signature of snow, flights were made over 3 snow covered sites by the NASA CV-990 Airborne Observatory in March 1971. The sites were Bear Lake on the Utah-Idaho border, the Yampa River Valley south of Steamboat Springs, Colorado, and the South Cascade Glacier and Lake in Washington. Ground truth measurements of snow depth and density were obtained at each of the three sites.

Ground based measurements (Edgerton et al. 1971, Meier and Edgerton, 1971) have indicated that for dry snow over frozen soil the effective microwave emissivity decreases as the snow pack increases. For example, at a wavelength of 8 mm and at a look angle of 45° the emissivity decreases from near unity for frozen soil to about 0.78 as a snow pack of density 500 kg/m is built up to a thickness of 80 cm. At longer wavelengths, the decrease was less for the same snow pack. The emissivity calculated for a very thick, uniform snow pack from the Fresnel equations (Jackson, 1962) is 0.97, so the bulk dielectric properties of snow cannot explain the low emissivity that was observed. The effect of liquid water in the snow on microwave emission from snow is striking. The emissivity at a wavelength of 8 mm increases from 0.78 to near unity (Edgerton et al., 1971) as the liquid water content of the surface layer increases from 0 to 1%. There effects are similar for both the vertical and horizontal polarizations.

The objective of these flights was to determine over what wavelength range the emissivity of dry snow is low and at what wavelengths the emission from a snow pack can be described by the bulk dielectric properties of snow. We also wish to determine the wavelengths for which the emissivity increases when liquid water is present in the snow.

The radiometers on-board the aircraft are listed in Table 1. The 1.55 cm radiometer scans $\pm 50°$ in a direction perpendicular to the aircraft's flight path. Thus, the radiation from a swath whose width is approximately twice the altitude of the aircraft above the ground is mapped. In addition, color infrared photography was obtained over each target and was used to determine the flight path of the aircraft.

## SUMMARY OF RESULTS

The brightness temperatures for all the radiometers from each target area are presented in Table 2. At Bear Lake and Steamboat Springs the values are averages for the total time over each target. The values from the Cascade Glacier are the averages for the periods (2-3 seconds) that the aircraft was over each specific area.

The results from the 0.8 cm and 1.55 cm radiometers exhibit the least amount of variation among the 3 target areas. This may result from the fact that the surface snow at each site had similar characteristics. The variation increases with wavelength indicating that these radiometers are responding to the variation in the substrata. The details of these variations will be discussed for each site individually in the following paragraphs.

## YAMPA RIVER VALLEY

Snow depth and density measurements were obtained along a 4 mile N S track in the Yampa River Valley South of Steamboat Springs Colorado. The snow depths ranged from 75 to 90 cm and the snow density ranged from

Table 1

Radiometer Characteristics

| Freq. GHz | Wavelength cm | Pointing Relative to Nadir | 3 db Beam Width | RMS Temp. Sens. | Reference |
|---|---|---|---|---|---|
| 1.42 | 21 | 0° | 15° | 5 K | Edgerton et al. (1971) |
| 2.69 | 11 | 0° | 27° | 0.5 K | Gray et al. (1971) |
| 4.99 | 6.0 | 0° | 5° | 15 K | Edgerton et al. (1971) |
| 10.69 | 2.8 | 0° | 7° | 1.5 K | Wilheit et al. (1972) |
| 19.35 H | 1.55 | SCANNER | 2.8° | 1.5 K | Oister and Falco (1967) |
| 37 V | 0.81 | 45° | 5° | 3.5 K | Wilheit et al. (1972) |
| 37 H | 0.81 | 45° | 5° | 3.5 K | Wilheit et al. (1972) |
| INFRARED | 10 microns | 14° | <1° | <1 K | Kuhn et al. (1971) |

Table 2

Observed Brightness Temperatures, in Kelvins

| | Snow Thickness (m) | 21 cm | 11 cm | 6 cm | 2.8 cm | 1.55 cm | 0.8 cm Horiz. | 0.8 cm Vert. | IR |
|---|---|---|---|---|---|---|---|---|---|
| Bear Lake<br>Alt. 1805 m | .15 | 123 | 156 | 163 | 193 | 206 | 198 | 231 | -5°C |
| Steamboat Springs<br>Alt. 2070 m | .8 | 212 | 235 | 246 | 243 | 215 | 211 | 235 | -7°C |
| South Cascade Glacier | | | | | | | | | |
| South Cascade Lake[1]<br>Alt. 1610 m | .5 | 222 | 252[2] | 242 | 250 | 232 | 232 | 255 | -2°C |
| P-0 - below firn line<br>Alt. 1770 m | 4.9 | 247 | 258 | 244 | 241 | 205 | 208 | 235 | -2°C |
| P-1 - above firn line<br>Alt. 1890 m | 6.8 | 242 | 256 | 238 | 231 | 202 | 214 | 238 | -5°C |
| P-3<br>Alt. 2040 m | 8.4 | 239 | 252 | 231 | 224 | 194 | 206 | 235 | -5°C |
| Chickamin Glacier<br>Alt. 2310 m | | 234 | 246 | 231 | 235 | 210 | 218 | 238 | -8°C |

1) Values at 21 and 11 cm are for the lowest altitude pass only.
2) Field of view includes areas of dry snow on slopes bordering lake. .

260-330 kg/m$^3$. The ground beneath the snow was not frozen and the soil moisture was generally greater than 35%, by weight.

The results presented in Table 2 are from a flight at a altitude of 4000 m above the ground on March 3, 1971. The ground was partially visible during the overflight because of cloudy conditions.

The most interesting result is the low brightness temperature of 212 K at a wavelength of 21 cm. This temperature is about that seen for very moist argicultural fields (Schmugge et al., 1973) and thus it appears that the snow is transparent at this wavelength. The brightness temperatures at 0.8 cm (horizontal polarization) and 1.55 are as low as those observed in the ground measurement of Edgerton et al. (1971).

## BEAR LAKE

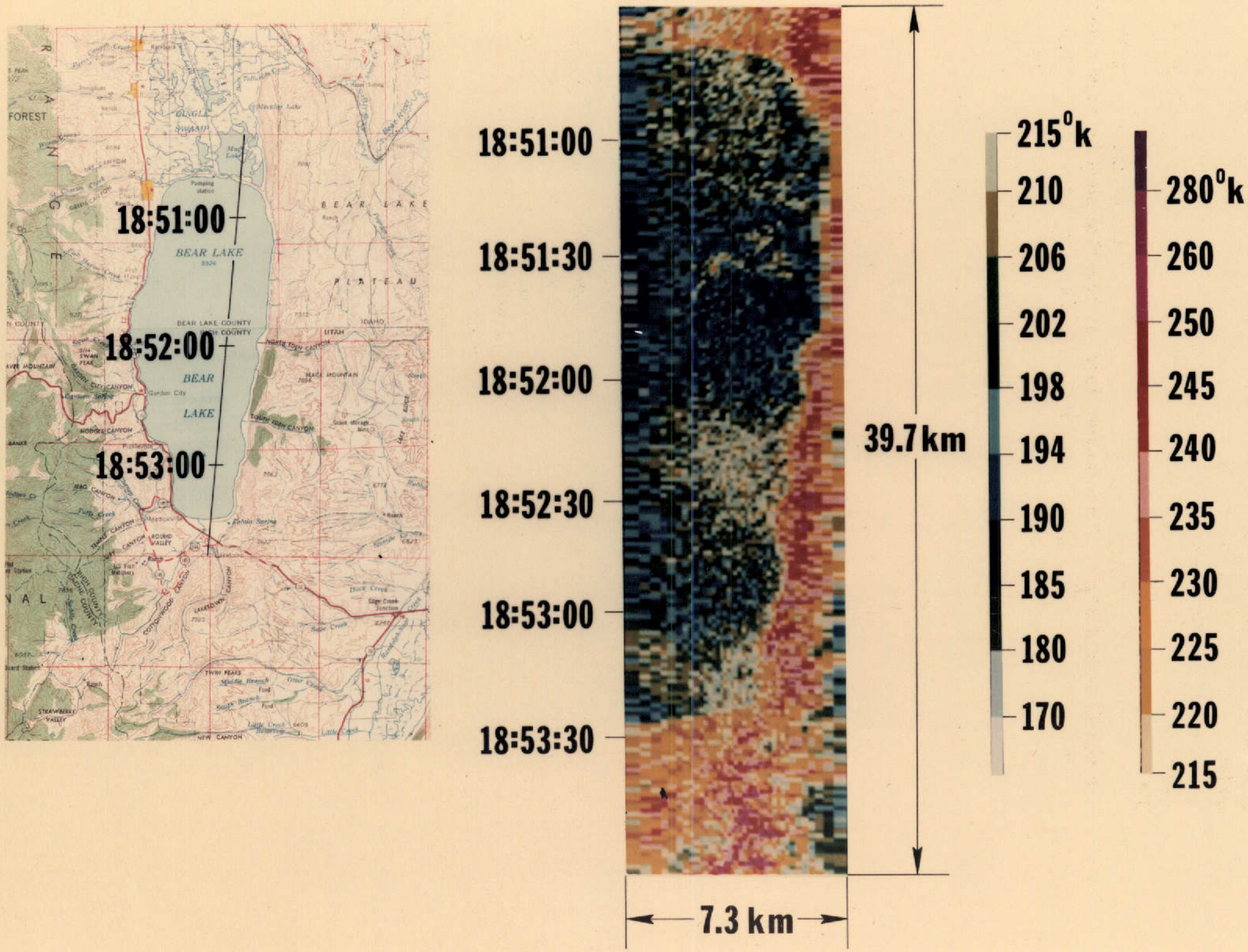
The surface of Bear Lake is at an altitude of 1800 m. The ground truth site was selected to be representative of the whole lake. It was located 700m from the Limnological Laboratory of Utah State University. The depth of snow was measured over a 12,000m$^2$ (3 acre) site and ranged from 13 to 17 cm, having an average of 15 cm. The average density of the snow was 200 kg/m$^3$. This snow fell about one week before the flight. During the intervening period the snow temperature stayed below freezing and there was little or no wind which would have packed the snow. The albedo of the snow was high (0.86) indicative of new snow. The ice thickness at this location was 25 cm.

Figure 1 is the microwave image of the pass over Bear Lake at an altitude of 3400 m above the terrain along with a map of the area on which the flight line is plotted. The pass was from north to south at a speed of 185 m/sec. The eastern edge of the lake has a steep slope with areas of exposed rock having a higher brightness temperature, 245 K, than the snow covered lake. In general, the brightness temperature of the lake was 194-210 K except for a region with a value of about 190 K between 18:51:30 and 18:52:00 which corresponded to an area with a large number of cracks in the ice.

The stripchart results from all the radiometers for this pass over Bear Lake are shown in Figure 2. The plot for the 1.55 cm radiometer is the average of the center 5 beam positions from the data presented in the image shown in Figure 1. The sharp drop observed by the longer wavelength radiometers, 60 K at 2.8 cm and 120 K at 21 cm, can be understood quantitatively using a straightforward layered model.

The reflectivity of a layered dielectric may be calculated as a boundary value problem according to the principles found in electromagnetic theory texts such as Jackson (1962). Assuming a uniform thermodynamic temperature this result can be expressed as a brightness temperature. In this case, we treat four layers: air, snow, ice and water. The dielectric constants for snow and ice are given by Evans (1965) and for water by Lane and Saxton (1952). Using these data and assuming a density of 200 kg/m$^3$ for the snow and a temperature of 273 K for the water, we get the dielectric constants given Table 3.

# 1.55 CM MICROWAVE IMAGE OF BEAR LAKE
## MARCH 3, 1971



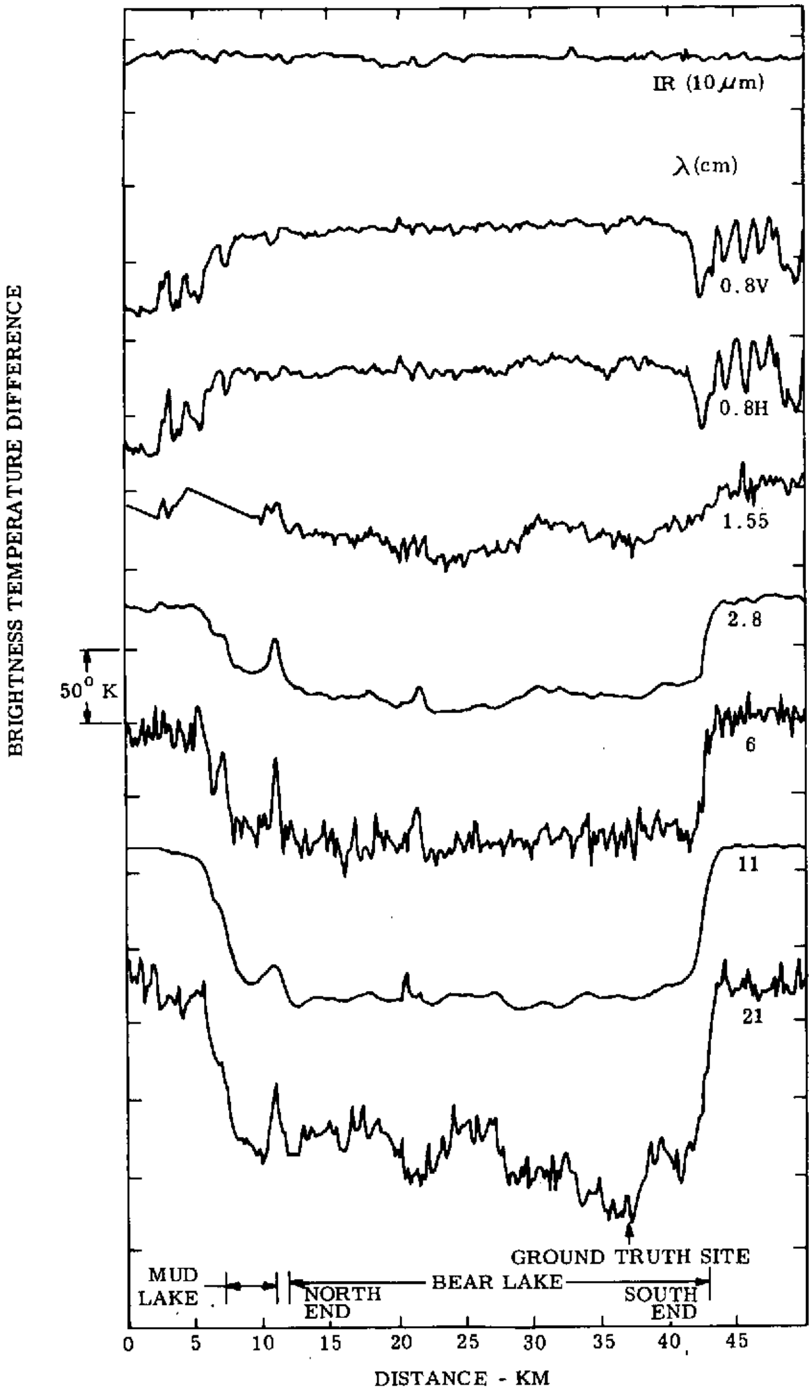



Figure 2. Multispectral data obtained over Bear Lake. The H and V refer to the horizontal and vertical channels of the 0.8 cm radiometer which viewed the surface at an angle of 45°. The remaining radiometers were nadir viewing. Average values for the brightness temperatures over the lake at each frequency are given in Table 2.

Table 3

Dielectric Constants For Bear Lake Calculation

| Layer | Dielectric Constant at 21 cm | Dielectric Constant at 11 cm |
|---|---|---|
| AIR | 1.00 + 0 i | 1.000 + 0 i |
| SNOW | 1.32 + .0002 i | 1.32 + .0002 i |
| ICE | 3.2 + .004 i | 3.2 + .004 i |
| WATER | 85.4 + 13.3 i | 80.3 + 23.6 i |

Since the imaginary components for the ice and snow layers are small, the calculation is not sensitive to the exact value nor to the temperature of the layer; we have accordingly assumed a temperature of 273 K for all layers. The results of such a calculation are shown in Figure 3 as contours of constant brightness temperature for the 21 cm channel as a function of ice thickness and of snow thickness. The contours are 120 K, 160 K and 200 K.

The brightness temperature is a strong function of the ice thickness with a weaker snow thickness dependence modulating the amplitude of the ice thickness dependence.

A similar calculation was performed for the 11 cm channel. The results were virtually identical except for the reduced wavelength of the interference effects. The snow thickness/ice thickness combinations consistent with the observed brightness temperature at both 21 and 11 cm are indicated by the shaded regions in Figure 3. The measured snow and ice thicknesses at the surface truth site (with uncertainties of 1 cm) are indicated by the black square; this is in good agreement with one of the possible combinations of snow and ice thickness consistent with the radiometer data.

We believe that the observed variability in the 11 and 21 cm data over the lake is related to ice and/or snow thickness variation. The maximum variability in the ice thickness consistent with the variation of the 11 cm radiometer (± 5 K) is 2 mm when averaged over an area determined by the beamwidth the instrument, a circle of approximately 800 m radius. Because of the weakness of the snow effect, no limit can be placed on the snow thickness variability.

## SOUTH CASCADE GLACIER

At South Cascade Glacier, the snow surface was very smooth with only small snow dunes. Snow at the surface was soft and light with a density of 250 kg/m$^3$, increasing with depth. Ground truth measurements had been made one week before the overflight and air temperature, precipitation and runoff were recorded through the time of overflight. Three relatively level points on the glacier and on South Cascade Lake north of the glacier were selected for analysis. The total snow depth at P-0, altitude 1770 m, a point below the firn line near the terminus of the glacier, was 4.9 m over the ice. At P-1, altitude 1890 m, a point slightly above the firn line near the center of the glacier, the snow depth was 6.8 m over firn. The total snow, firn and

21 CM BRIGHTNESS TEMPERATURE CONTOURS 40° K INTERVALS

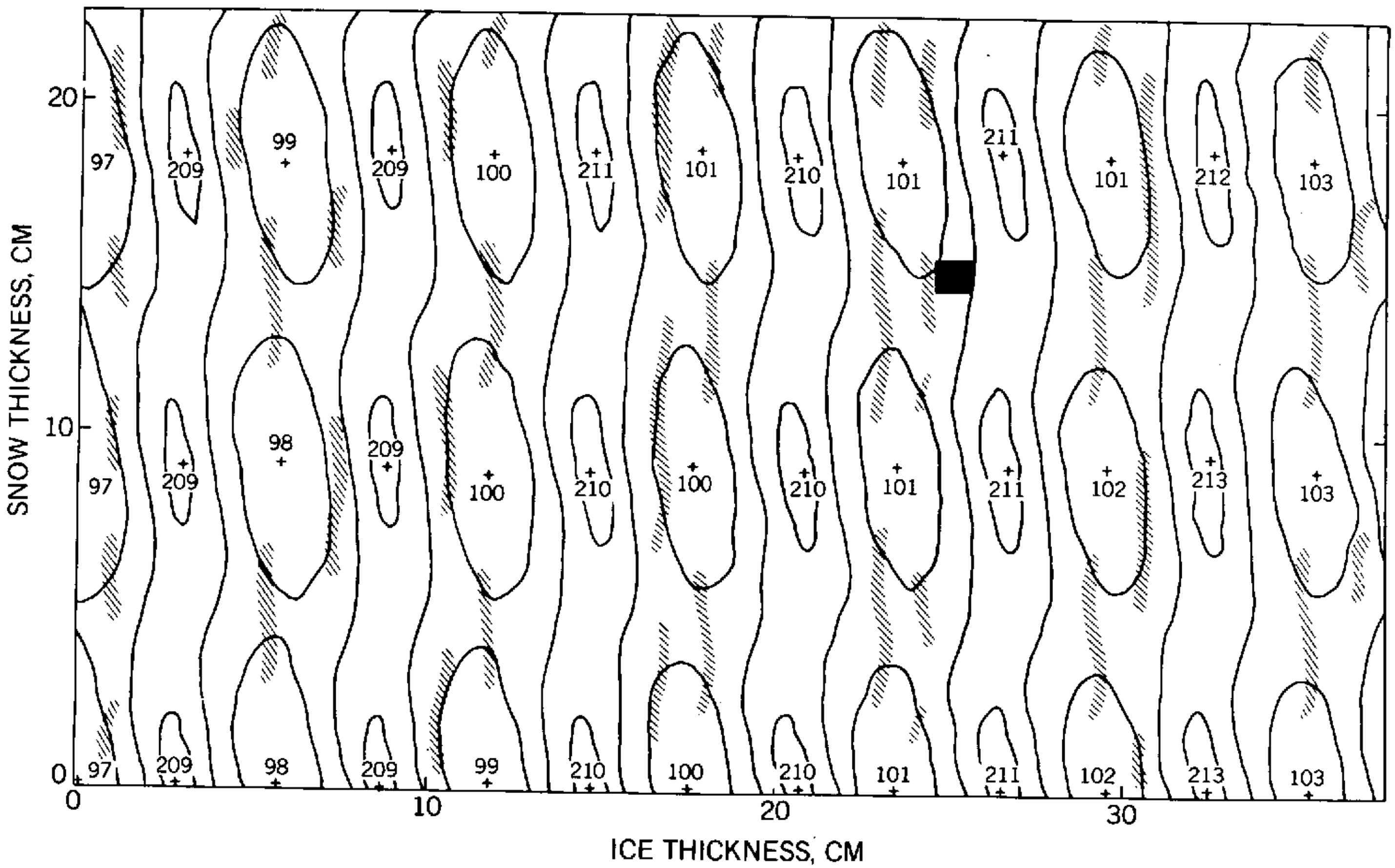



Figure 3. Calculated brightness temperature contours for the 21 cm radiometer as a function of snow and ice thicknesses. The 120 K, 160 K, and 200 K contours are drawn. The shaded areas are those where the calculated 21 cm and 11 cm brightness temperatures are consistent with their observed values. The black square is the range of observed snow and ice thicknesses at Bear Lake.

ice depth was over 200 meters at this point. A third location, P-3, altitude 2040 m, had a snow depth of 8.4 m over the firn layer. The temperature records indicate that there was no liquid water in the top meter of snow at any point on the glacier.

At the fourth ground truth site, South Cascade Lake, there was a transition layer, approximately 0.5 m thick, of light snow containing some liquid water. This layer was below about 0.2 m of light dry snow and above 3 m of wet snow, slush and water. This was the only site with any wet snow present. The Chickamin Glacier 3 km southeast of the South Cascade Glacier was also over-flown. While no ground truth was obtained at this glacier it did provide another high altitude (2300 m) snow target with steeper slopes, thicker and colder snow and more surface roughness than the South Cascade Glacier.

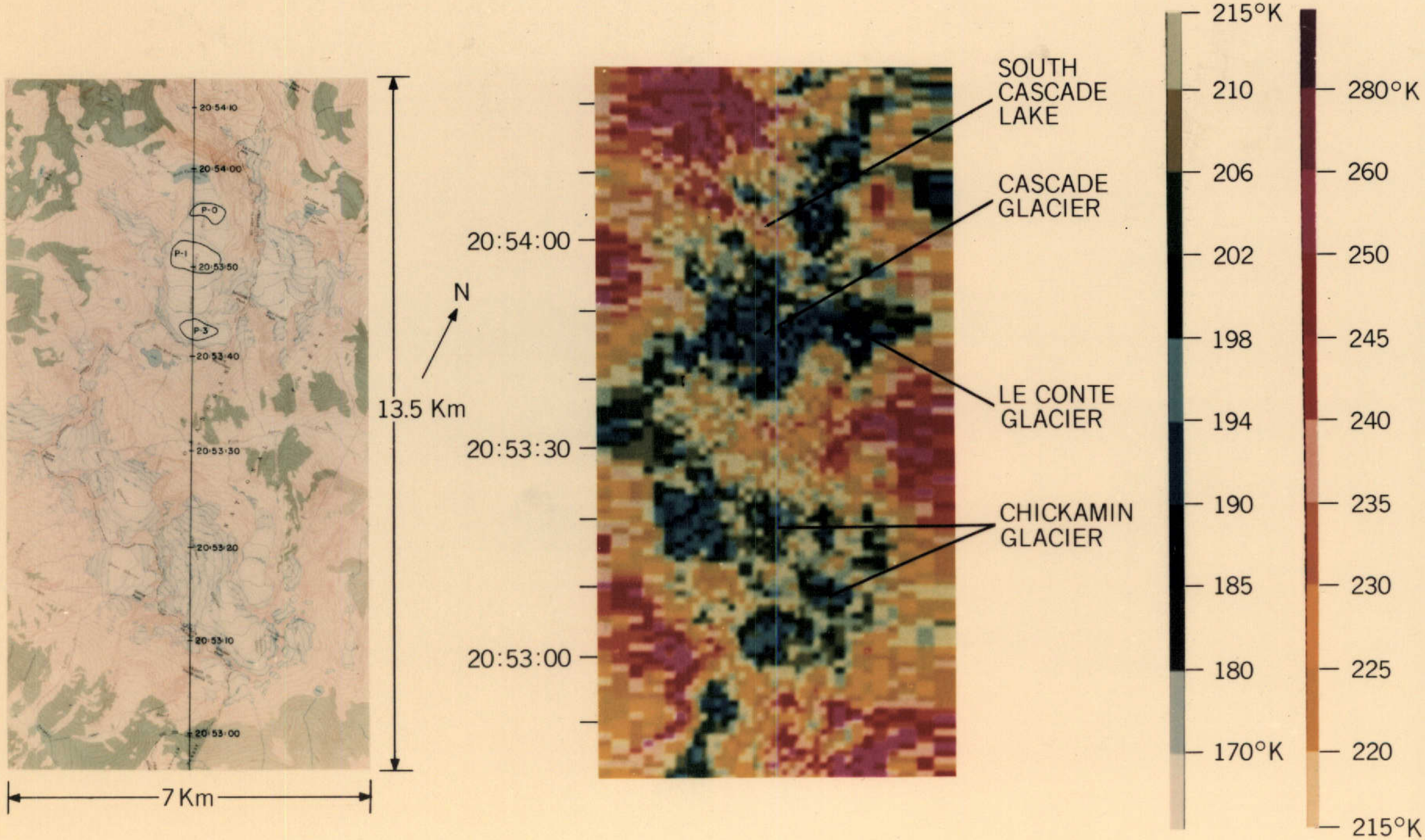
The aircraft made three passes over the glacier at altitudes of 3330 m, 3420 m, and 4830 m above sea level. The results from the three passes were consistent within the noise levels of the radiometers. The values presented in Table 2 are the averages for these passes.

In Figure 4, the microwave image of the South Cascade Glacier area from the 4830 m pass, the blue and dark green areas are those with the lowest brightness temperatures and these areas approximately correspond to the glaciers. Some of the glaciers which can be located on the microwave image are the South Cascade, Chickamin, LeConte, Dome, Dana and Spire. Generally the brightness temperatures of the glaciers are below 205 K. The snow-covered mountain slopes, e.g. the area between the Cascade and Dana glaciers, have brightness temperatures in the range 210-225 K, indicated by yellow and light green in the microwave image. The high brightness temperature areas, violet and red (240-255K), are forested areas where there is a foliage canopy above wet snow.

South Cascade Lake shows a somewhat higher brightness temperature, about 230 K, than that of the glacier. A 15 to 20 K rise was also observed in the horizontal and vertical channels of the 0.8 cm wavelength radiometer. These increases in the brightness temperature of the snow are possible indications of the presence of liquid water in the snow, in agreement with the surface observation. The 21 cm radiometer has a lower brightness temperature for the lake which may be indicative of its ability to penetrate a sufficiently thin wet snow layer.

On the glacier itself the shorter wavelength radiometers (1.55 cm and 0.8 cm) had the lowest brightness temperatures while the 21 and 11 cm wavelength radiometers had the highest brightness temperatures. The results at the longer wavelengths can be understood in terms of the same layered dielectric model used with the Bear Lake results. In this case, the observed snow density was used to calculate its dielectric constant using the Weiner mixing formula (Evans, 1965). At P-0 the snow density increased linearly from 250 kg/m$^3$ at the surface to 500 kg/m$^3$ at a depth of 4.9 meters at which point the ice begins. For a surface temperature of 270 K the calculated brightness temperature is 265 K which is in good agreement with the 258 K value observed by the 11 cm radiometer which was the most accurate of the radiometers. Instrument uncertainties preclude determining how well the 21 and 6 cm results agree with the calculation. At the shorter wavelengths the brightness temperatures are substantially below the calculated results.

# 1.55 CM MICROWAVE IMAGE OF SOUTH CASCADE GLACIER AREA MARCH 8, 1971



At 2.8 cm, the brightness temperatures range from 241 K to 224 K as the altitude increases on the glacier. The brightness temperatures at wavelengths of 1.55 cm and 0.8 cm (horizontal polarization) are below 210 K yielding emissivities of 0.8 or less. This is essentially the same spectral response as that observed for the emissivity difference between first year and multiyear sea ice (Gloersen et al. 1973), Wilheit et al. 1972) radiometer, i.e. there was no difference observed in the 6 cm, 11 cm and 21 cm results while the difference increased as the wavelength decreased from 2.8 cm to 0.8 cm. As was the case with the multi-year ice we expect that the low emissivities result from volume scattering occurring in the snow and firn layers on the glacier. The scattering centers in this case are suspected to be the ice grains. The strength of the scattering depends on the wavelength in ice, increasing as this wavelength becomes comparable to or less than, the size of the scattering centers. At wavelengths much larger than these centers e.g. 11 and 21 cm, volume scattering is unimportant and the medium can be described by its bulk dielectric properties.

Since our experiments could not differentiate between the fresh snow and firn layers on the glacier, we have no measure of the difference in scattering cross-sections in these media, but we suspect that it is proportional to the water equivalent of the medium, as has been suggested by earlier results (Edgerton et al. 1971). The low values of brightness temperature observed 0.8 and 1.55 cm over the Cascade Glacier are consistent with K-band radar results (Waite and MacDonald, 1970), in which an increase of the scattering from old snow as compared to that of fresh snow or solid ice was observed.

Finally, it can be seen from the 0.8 cm data in Table 2 that the scattering cross-section appears to be polarization-dependent. However we are not certain about the significance of this result due to uncertainties about the relative calibration of the two channels.

## CONCLUSIONS

These results indicate that the effects of volume scattering in dry snow and firn become noticeable for free space wavelengths shorter than about 3 cm as had been observed earlier for multiyear sea ice (Wilheit et al., 1972 and Gloersen et al., 1973). When liquid water is present, the effective loss tangent for the snow increases to wash out the effects of volume scattering. This is the same mechanism that produces the higher brightness temperature at these wavelengths in first year sea ice when the scattering centers, brine cells, are filled with liquid.

At the longer wavelengths, 11 and 21 cm, the results at Bear Lake and the dry snow areas of Cascade Glacier are in good agreement with those calculated using the bulk dielectric properties of ice and snow, indicating that scattering may not be an important mechanism at these wavelengths.

These results are in reasonable agreement with the earlier ground-based measurements of microwave properties of dry and wet snow (Edgerton et al. 1971) and airborne observations at 1.55 cm (Meier, 1972). The rise in brightness temperature for wet snow indicates that it may be possible to detect the onset of snow melting by looking at brightness temperature differences between day and night passes over snow fields.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of A. Edgerton of Aerojet-General Corporation, J. C. Blinn III of Jet Propulsion Laboratory, in calibrating, installing, and operating various instruments aboard the NASA CV-990 (see Table 1). The authors wish to thank G. Hidy of North American and P. Kuhn of the NOAA Environmental Research Laboratories for the use of the data obtained with their instruments, Dr. Eugene Peck of the NOAA Hydrologic R&D Laboratory for providing the ground truth data at Steamboat Springs, and Earl Petersen and the CV-990 crew of the Ames Research Center for their support.

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